Center for Particle Cosmology at the University of Pennsylvania

# Screening Dark Energy

Justin Khoury (UPenn)

K. Hinterbichler & J. Khoury, Phys. Rev. Lett. 104, 231301 (2010)

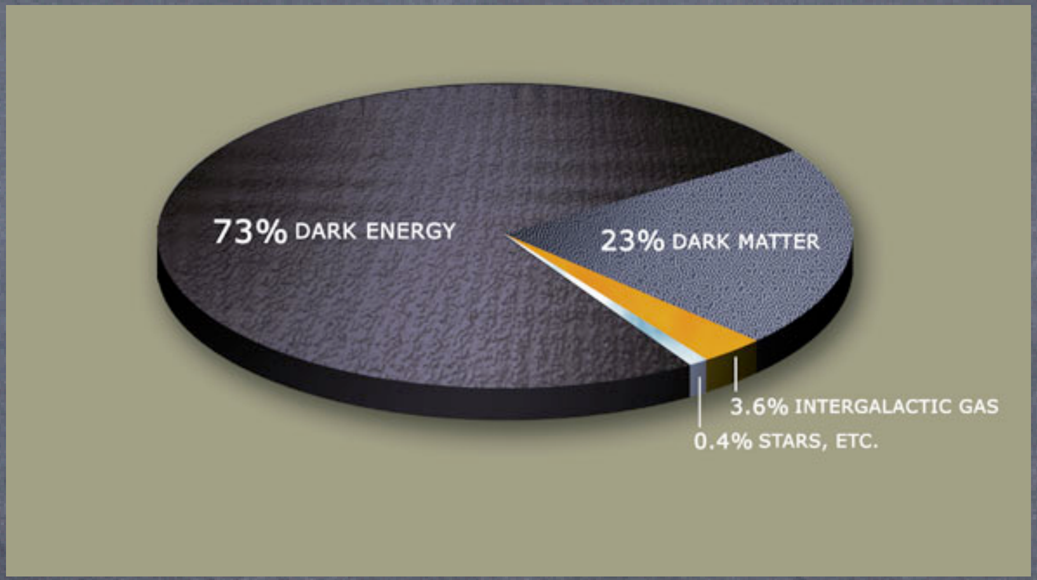
B. Jain & J. Khoury, Annals Phys. 325, 1479 (2010)

A. Levy, A. Matas, K. Hinterbichler and J. Khoury, in progress

Is it possible for light, gravitationally-coupled degrees of freedom to exist while avoiding detection from local experiments?

$$\phi$$

# 1. The Era of Precision Uncertainty




$$\Omega_b h^2 = 0.02260 \pm 0.053\,; \qquad \Omega_c h^2 = 0.1123 \pm 0.0035\,;$$

$$\Omega_\Lambda = 0.728 \pm 0.016 \qquad n_s = 0.963 \pm 0.012\,;$$

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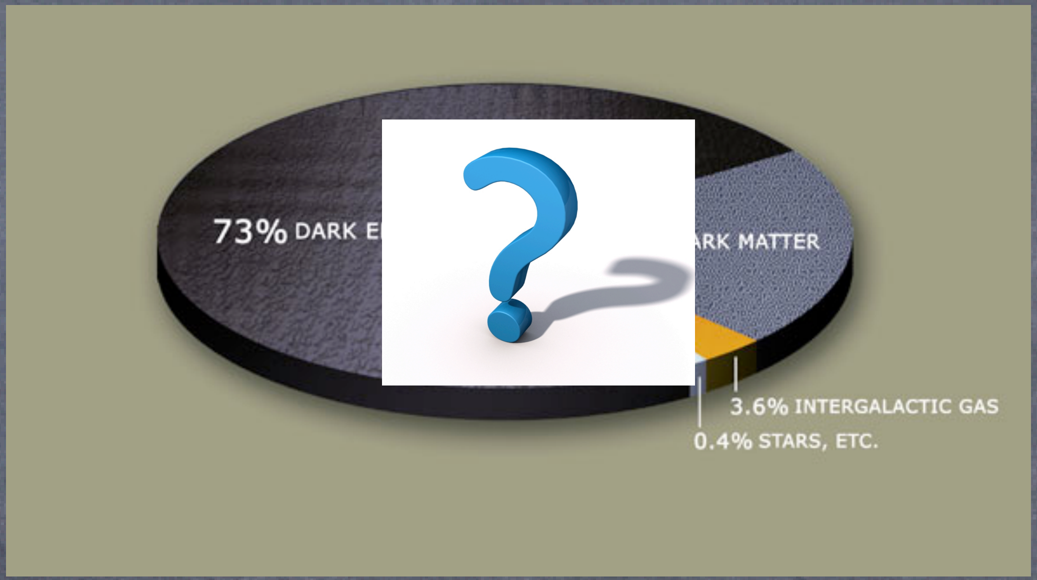


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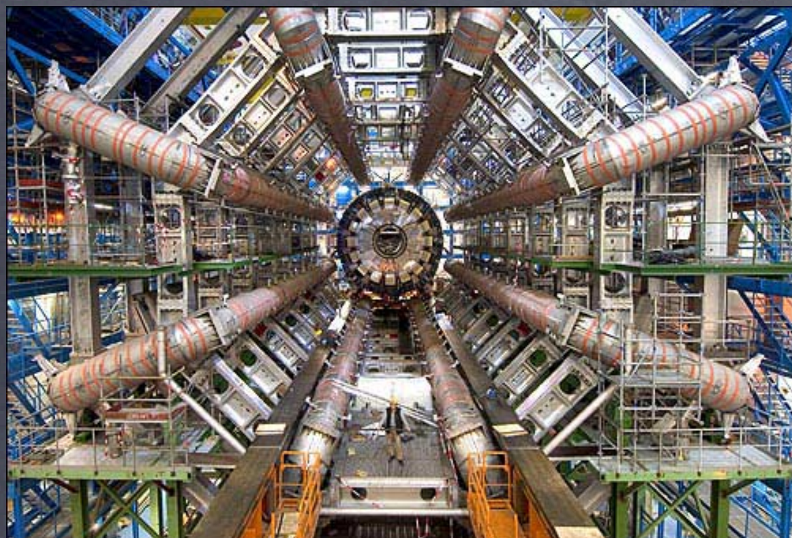

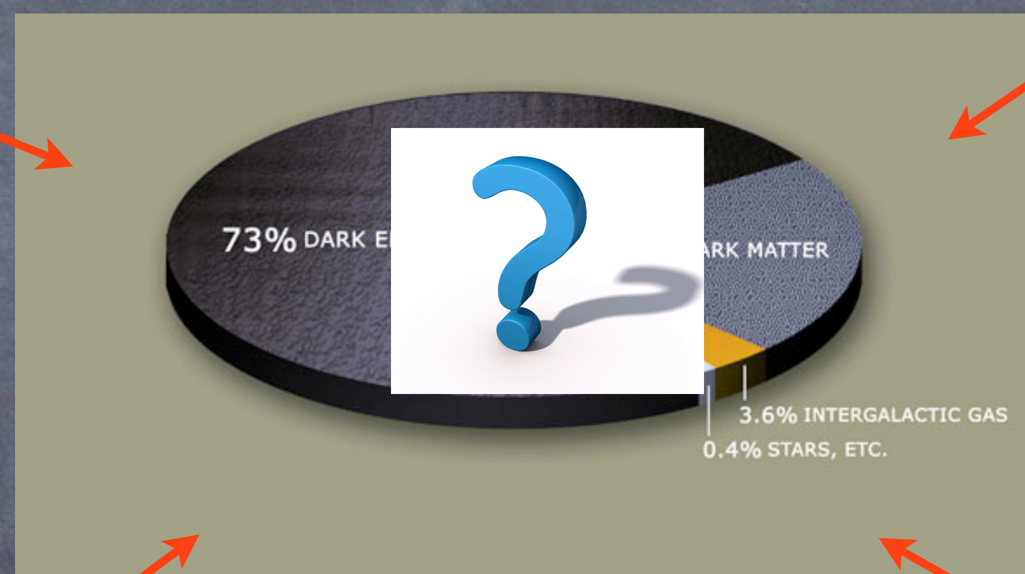


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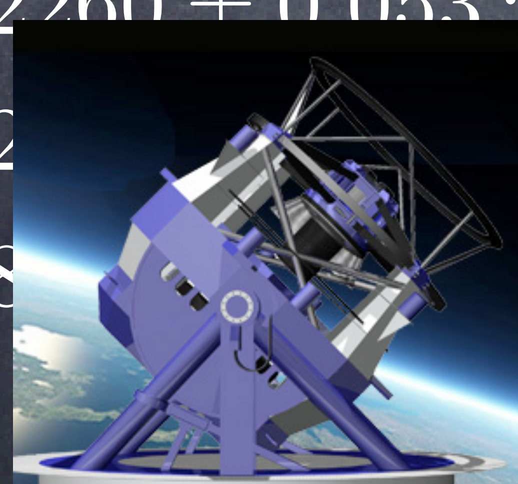
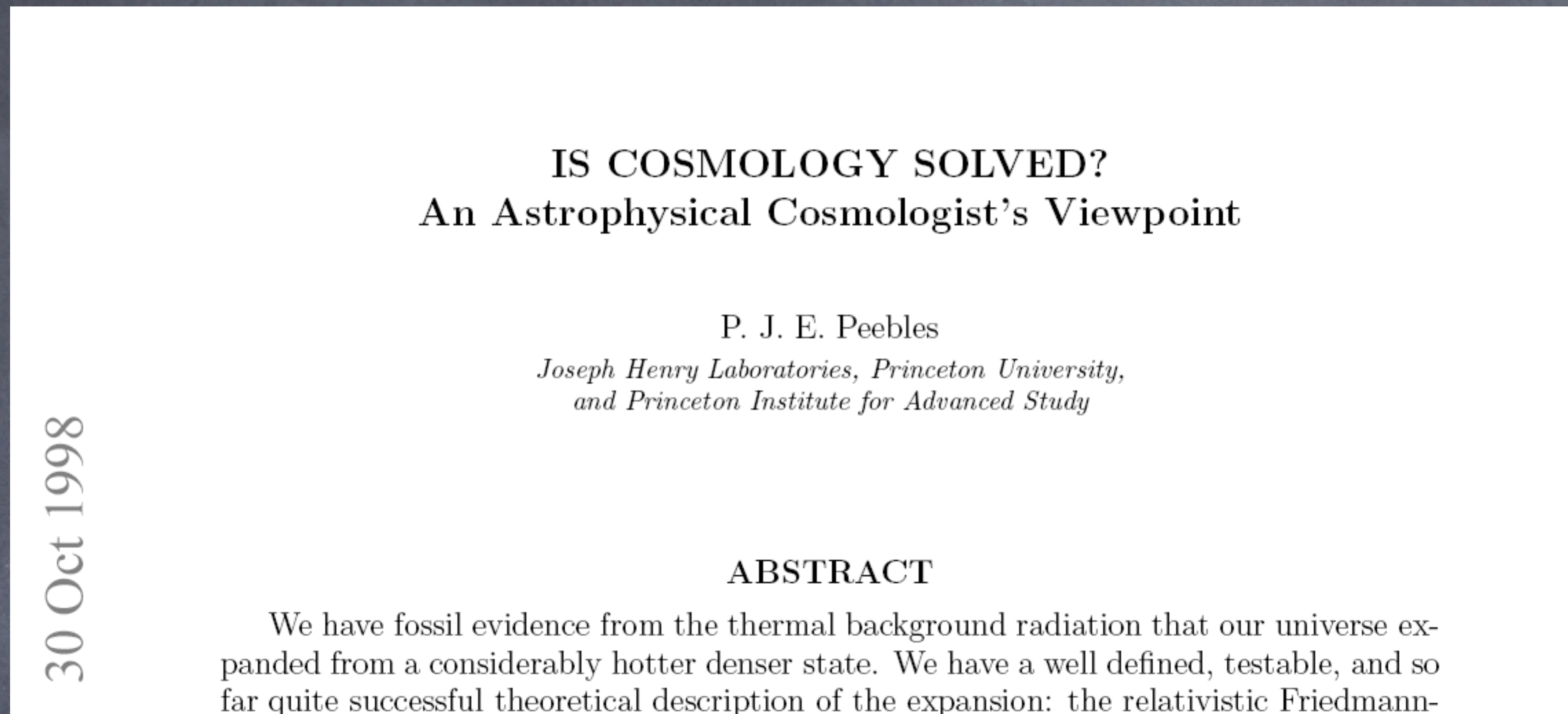


# The end of cosmology?



30 Oct 1998

IS COSMOLOGY SOLVED?
An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles

*Joseph Henry Laboratories, Princeton University, and Princeton Institute for Advanced Study*

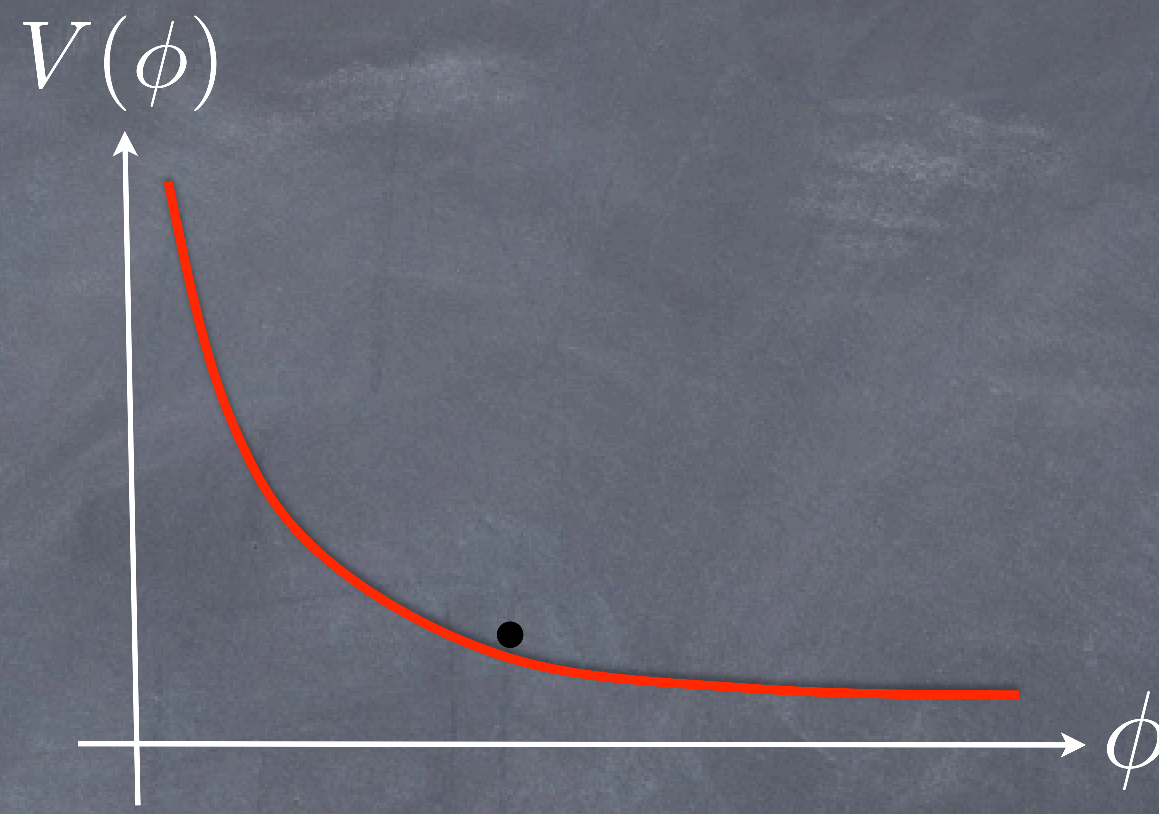
ABSTRACT

We have fossil evidence from the thermal background radiation that our universe expanded from a considerably hotter denser state. We have a well defined, testable, and so far quite successful theoretical description of the expansion: the relativistic Friedmann-

"Does $\Lambda$CDM signify completion of the fundamental physics that will be needed in the analysis of … future generations of observational cosmology? Or might we only have arrived at the simplest approximation we can get away with at the present level of evidence?"

\- Prof. P. J. E. Peebles

# A Richer Dark Sector




- Dark energy candidates:

  $\Lambda$, quintessence...

  Ratra & Peebles (1988); Wetterich (1988); Caldwell, Dave & Steinhardt (1998)

- Tantalizing prospect: quintessence (or any other light field) couples to both dark and baryonic matter.

  $\Longrightarrow$ ruled out?

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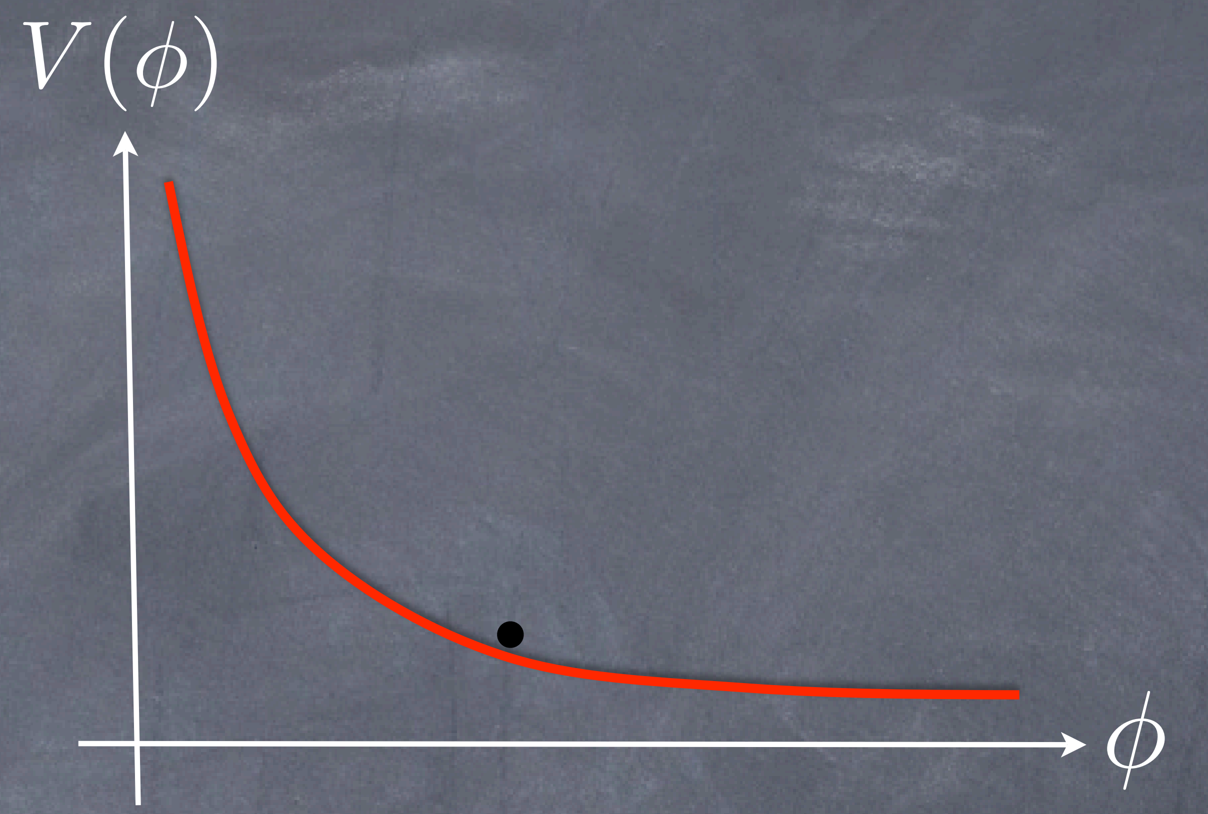


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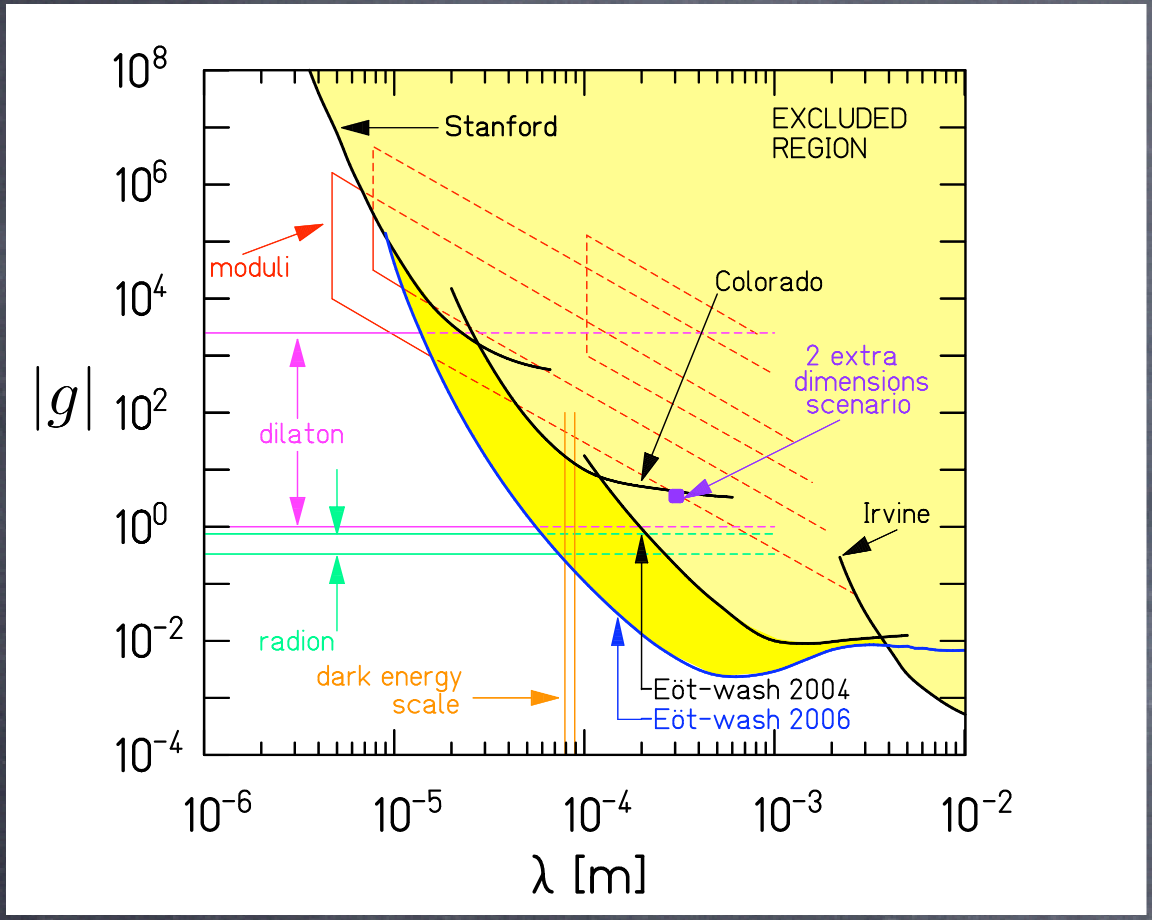
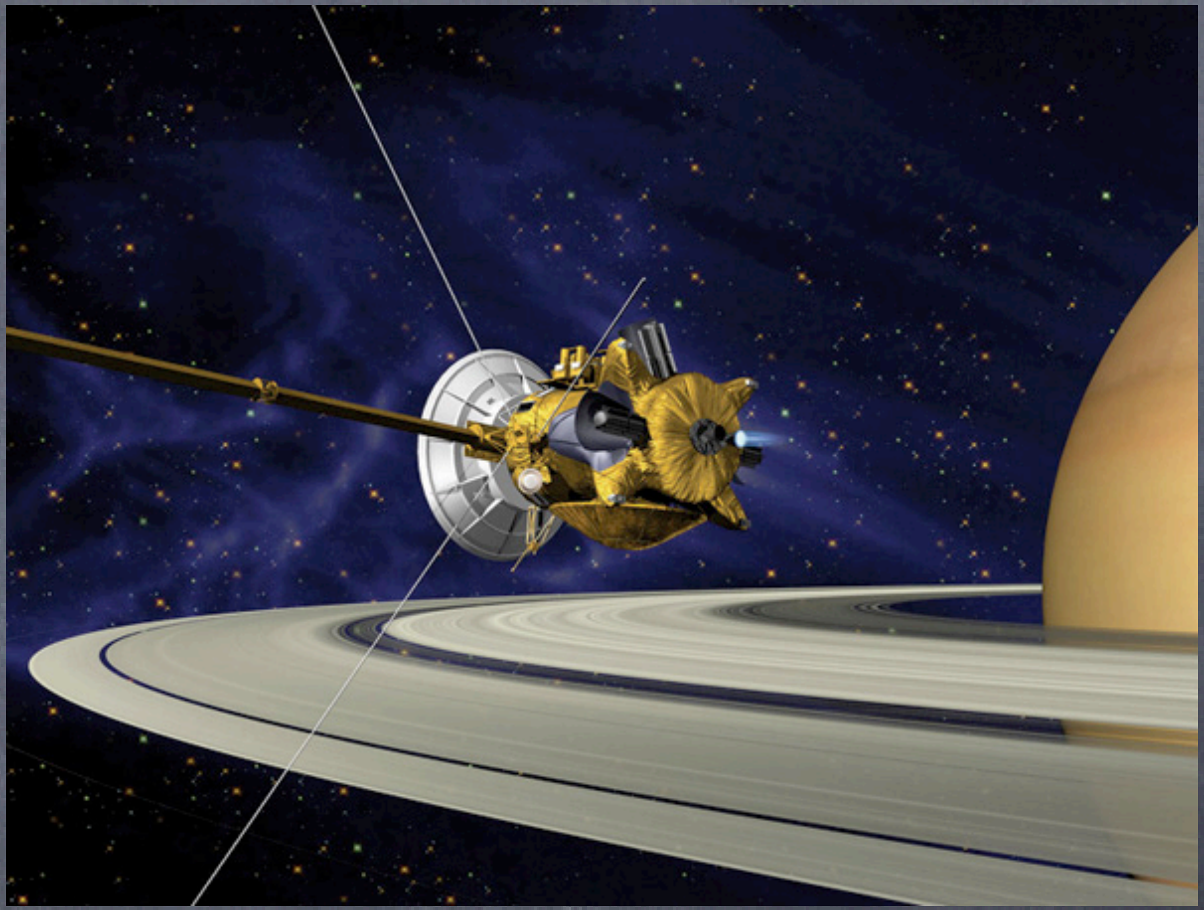
Not so fast. Scalar fields can "hide" themselves from local experiments through screening mechanisms

$$\boxed{\rho_{\rm here} \sim 10^{30}\rho_{\rm cosmos}}$$

# 2. Experimental Program

$$U(r) = -g \frac{M}{8\pi M_{\rm Pl}^2} \frac{e^{-r/\lambda}}{r}$$



Screening mechanisms invariably lead to small but potentially measurable effects in the solar system and/or in the lab

# The Wholistic Picture...

$$\nabla^2\phi + m^2\phi = -\frac{g}{M_{\rm Pl}}T^\mu_\mu$$

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$$\nabla^2 \phi + m^2 \phi = \frac{g}{M_{\rm Pl}} \rho$$

The Wholistic Picture...

$$\nabla^2\phi + \underbrace{M^2(\rho)}_{\text{chameleon}}\,\phi = \frac{g}{M_{\rm Pl}}\rho$$

# The Wholistic Picture...

$$K(\rho)\,\nabla^2\phi + m^2\phi = \frac{g}{M_{\rm Pl}}\rho$$

Vainshtein/galileon

# The Wholistic Picture...

$$\nabla^2\phi + m^2\phi = \frac{g(\rho)}{M_{\rm Pl}}\,\rho$$

symmetron

# Chameleon Mechanism

J. Khoury & Weltman, Phys. Rev. Lett. (2004);
Gubser & J. Khoury, (2004)

Consider scalar field $\phi$ with potential $V(\phi)$ and conformally-coupled to matter:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) + g\frac{\phi}{M_{\rm Pl}}T^{\mu}_{\mu}$$

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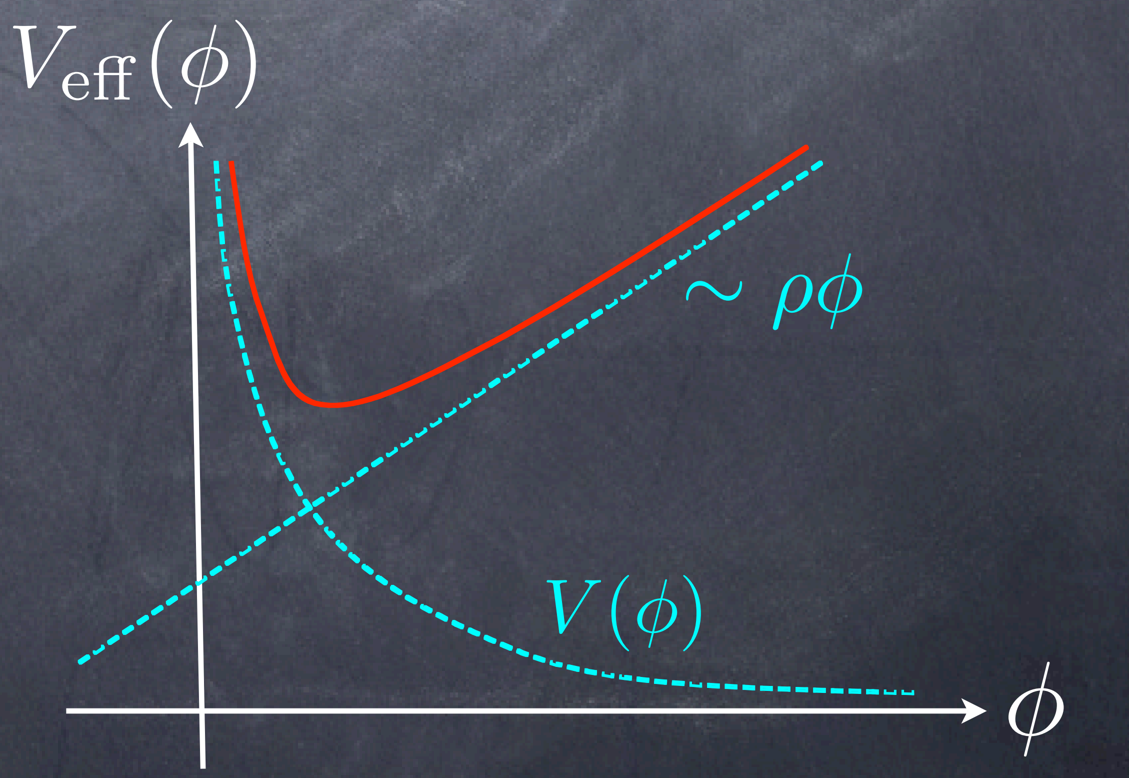
For non-relativistic matter, $T^\mu_\mu \approx -\rho$ , hence

$$\nabla^2\phi = V_{,\phi} + \frac{g}{M_{\rm Pl}}\rho$$

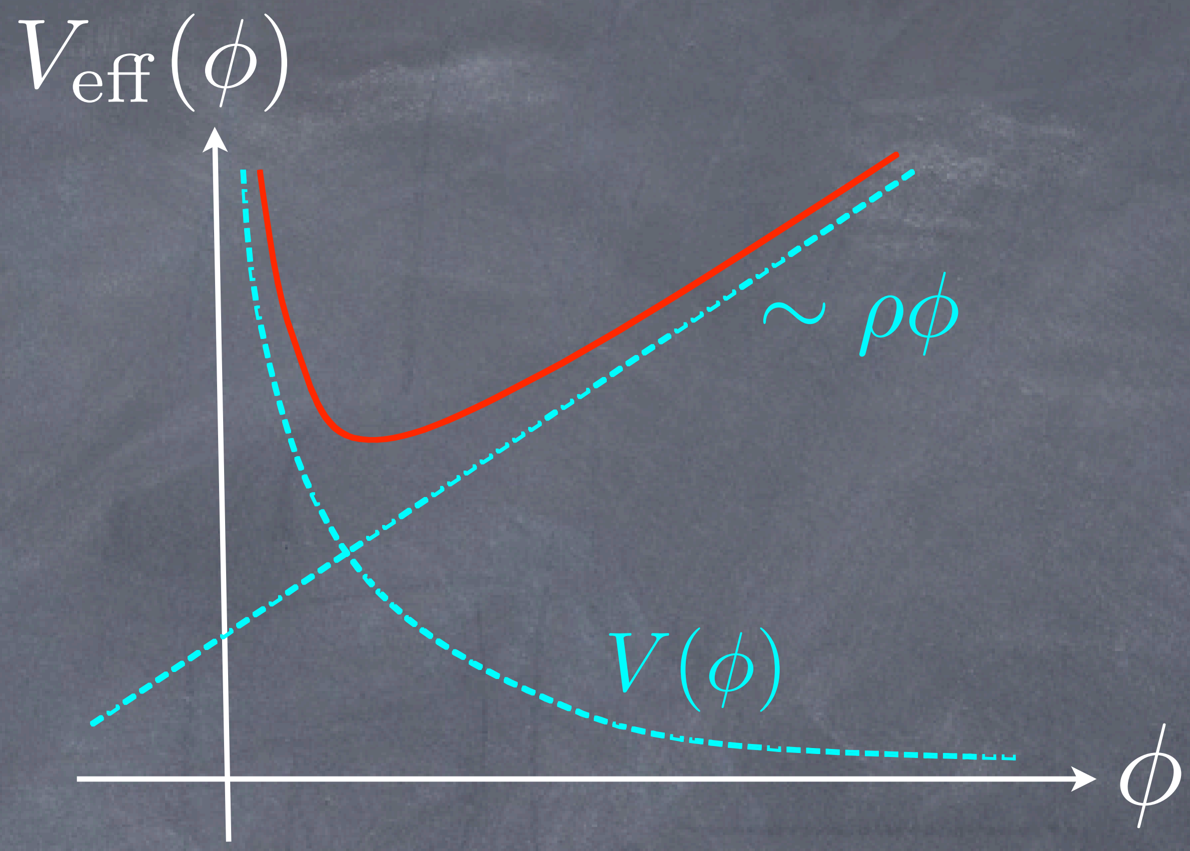
$$\Longrightarrow \quad \boxed{V_{\rm eff}(\phi) = V(\phi) + g\frac{\phi}{M_{\rm Pl}}\rho}$$



# Density-dependent mass

$$\boxed{V_{\text{eff}}(\phi) = V(\phi) + g\,\frac{\phi}{M_{\text{Pl}}}\rho}$$

e.g. $$V(\phi) = \frac{M^5}{\phi}$$




Thus $m = m(\rho)$ increases with increasing density

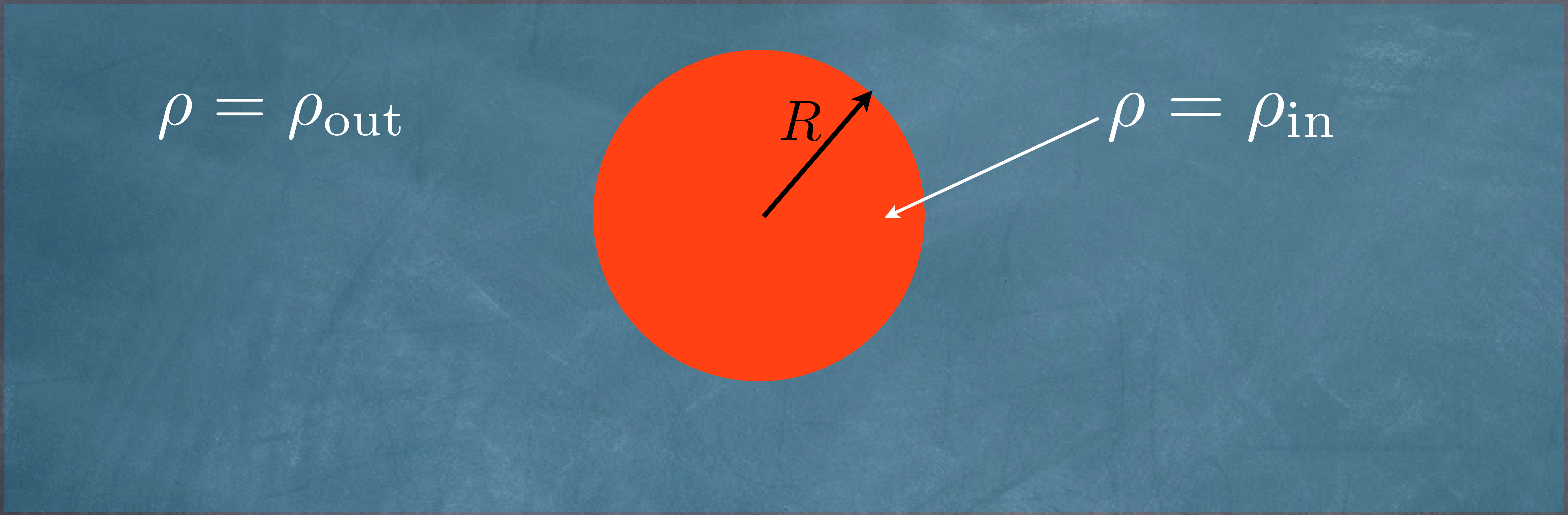
Laboratory tests => set $m^{-1}(\rho_{\text{local}}) \lesssim \text{mm}$

Generally implies: $m^{-1}(\rho_{\text{cosmos}}) \lesssim \text{Mpc}$

Meanwhile, $m^{-1}(\rho_{\text{solar system}}) \lesssim 10 - 10^4\ \text{AU}$

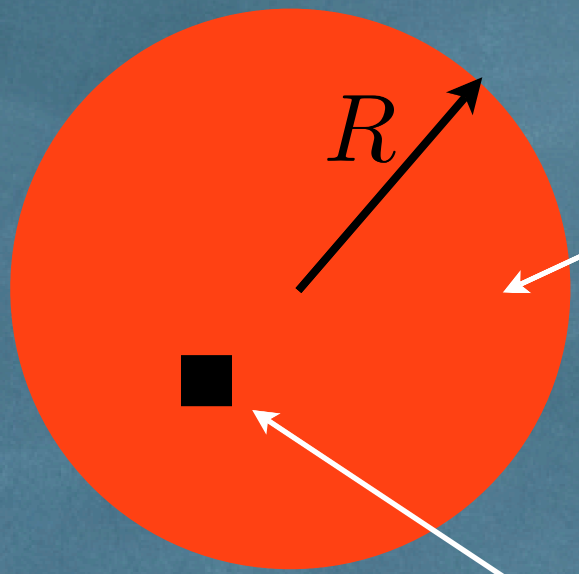
$\Longrightarrow$ ruled out by post-Newtonian tests?

# Thin-shell screening



# Thin-shell screening

$\rho = \rho_{\text{out}}$




$\rho = \rho_{\text{in}}$

$$\delta\phi \sim \frac{\delta\mathcal{M}}{r} e^{-mr}$$

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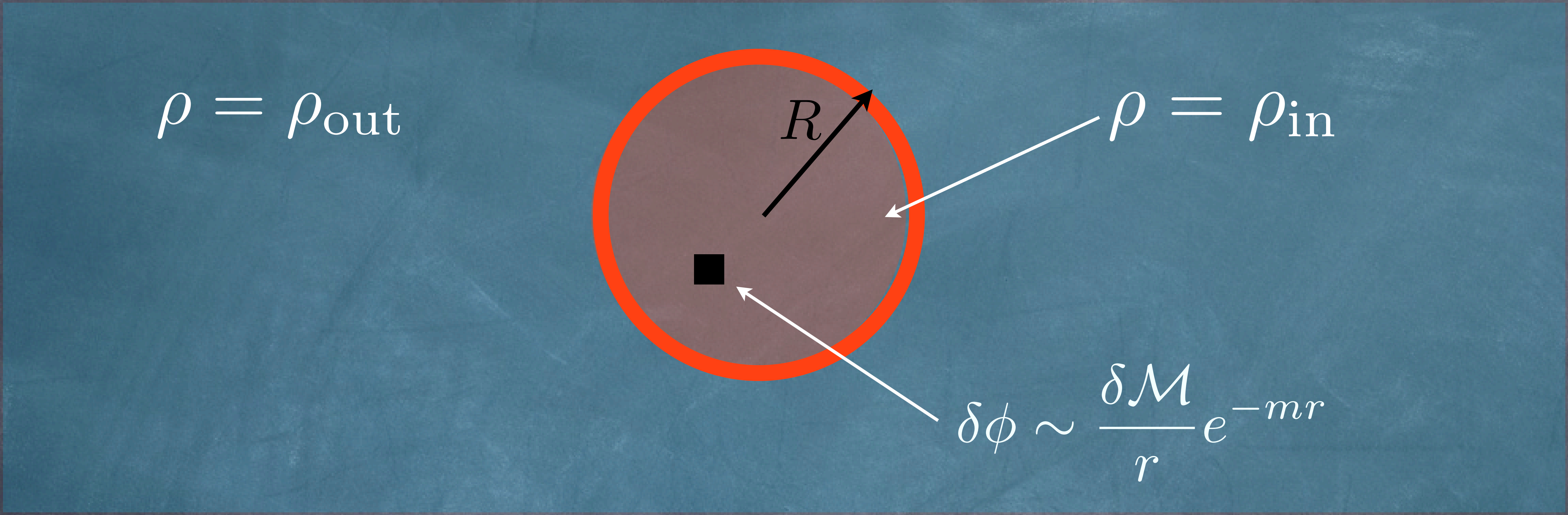

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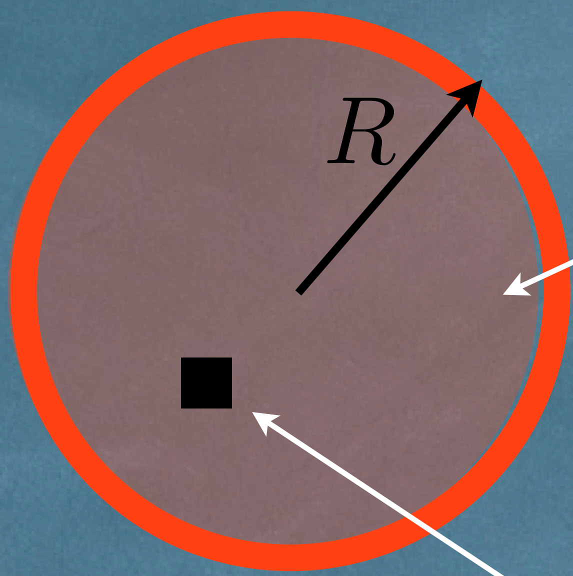


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$$\delta\phi \sim \frac{\delta\mathcal{M}}{r} e^{-mr}$$

$$\Longrightarrow \quad \boxed{\phi(r > R) \sim \frac{\Delta R}{R}\frac{g}{M_{\rm Pl}^2}\frac{\mathcal{M}}{r}}$$

where $\dfrac{\Delta R}{R} = \dfrac{\phi_{\rm out} - \phi_{\rm in}}{6 g M_{\rm Pl}\Phi_{\rm N}} \ll 1 \Longrightarrow$ thin-shell screening

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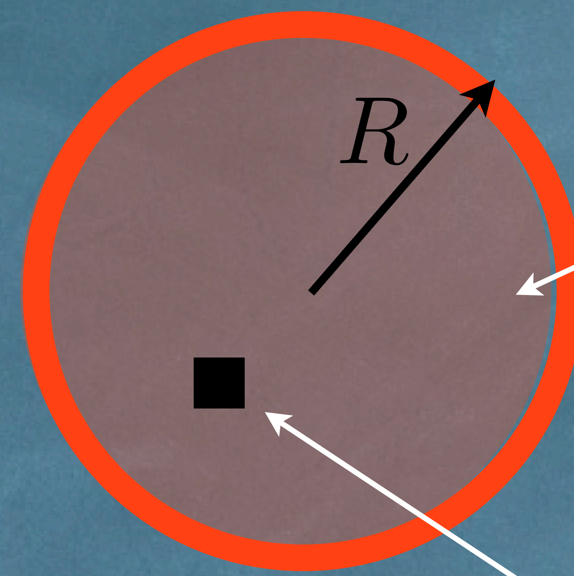


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But small objects $\Longrightarrow$ no thin-shell

$\Longrightarrow G_{\rm N}^{\rm eff} = G_{\rm N}(1 + 2g^2)$ in space !

# Smoking Guns

- STEP (???)

$$\frac{\Delta G_{\rm N}}{G_{\rm N}} < 10^{-6}$$

$$\downarrow$$

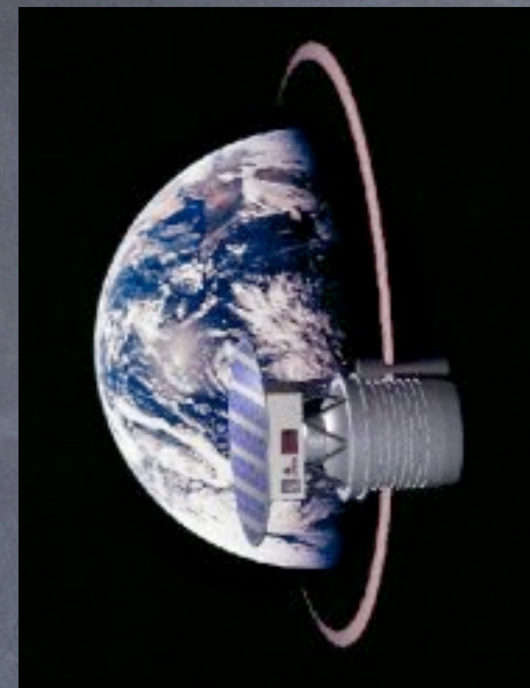
$$\frac{\Delta G_{\rm N}}{G_{\rm N}} \sim \mathcal{O}(1)$$

# Smoking Guns

- STEP (???)

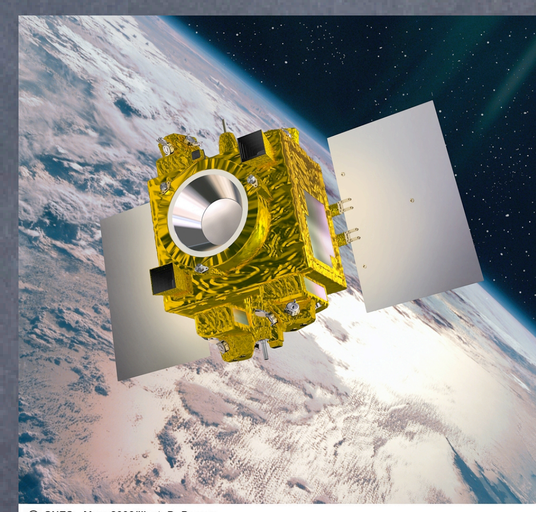
$$\frac{\Delta G_{\rm N}}{G_{\rm N}} < 10^{-6}$$

$$\frac{\Delta a}{a} < 10^{-18}$$



- MICROSCOPE (2012)

$$\frac{\Delta a}{a} < 10^{-15}$$




- Galileo Galilei (???)

$$\frac{\Delta a}{a} < 10^{-17}$$

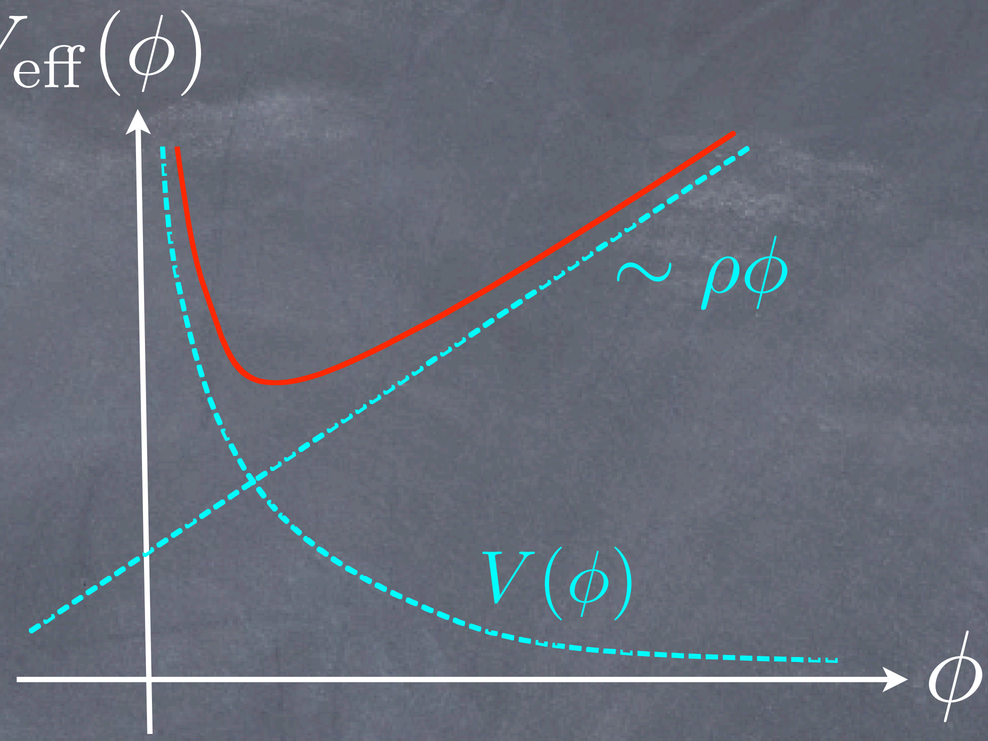
$$\frac{\Delta G_{\rm N}}{G_{\rm N}} \sim \mathcal{O}(1)$$

$$\frac{\Delta a}{a} > 10^{-13}$$

# Strong coupling?

J. Khoury, A. Upadhye & W. Hu, to appear

$$V(\phi) = \frac{M^5}{\phi} \qquad M = 10^{-3}\ \mathrm{eV}$$




Perturb around minimum:

$$V = \bar{V} + \ldots + \frac{\delta\phi^n}{\Lambda^{n-4}} + \ldots$$

where

$$\frac{\Lambda}{M} = \left(\frac{\bar{\phi}}{M}\right)^{\frac{n+1}{n-4}} = \left(\frac{M^2}{m^2}\right)^{\frac{n+1}{3(n-4)}} > \left(\frac{M^2}{m^2}\right)^{\frac{1}{3}}$$

- Cosmologically: $m \sim \mathrm{Mpc}^{-1} \Longrightarrow \Lambda \sim 10^5\ \mathrm{GeV}$
- Lab: $m \sim 10^{-3}\ \mathrm{eV} \Longrightarrow \Lambda \sim 10^{-3}\ \mathrm{eV}$

# Relation to f(R) gravity

Carroll, Duvvuri, Trodden & Turner (2004);
Capozziello, Carloni & Troisi (2004)

$$S = \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\sqrt{-\tilde{g}}f(\tilde{R}) + S_{\rm matter}[\tilde{g}_{\mu\nu}]$$

Special case of chameleon theories:

$$S = \frac{M_{\rm Pl}^2}{2}\int {\rm d}^4x\sqrt{-\tilde{g}}\left\{f(\psi) + \frac{{\rm d}f}{{\rm d}\psi}(\tilde{R}-\psi)\right\} + S_{\rm matter}[\tilde{g}_{\mu\nu}]$$

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Field redefinitions: $g_{\mu\nu} = \frac{{\rm d}f}{{\rm d}\psi}\tilde{g}_{\mu\nu}$ ; $\phi = -\sqrt{\frac{3}{2}}M_{\rm Pl}\log\frac{{\rm d}f}{{\rm d}\psi}$

$$\Longrightarrow S = \int {\rm d}^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[g_{\mu\nu}e^{\sqrt{2/3}\phi/M_{\rm Pl}}\right]$$

where $$V = \frac{M_{\rm Pl}^2\left(\psi\frac{{\rm d}f}{{\rm d}\psi} - f\right)}{2\left(\frac{{\rm d}f}{{\rm d}\psi}\right)^2}\,.$$

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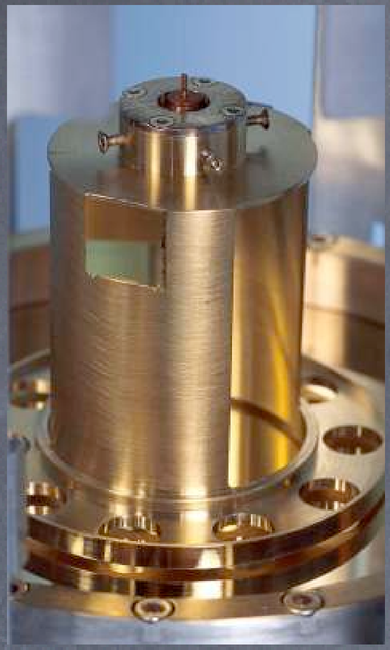
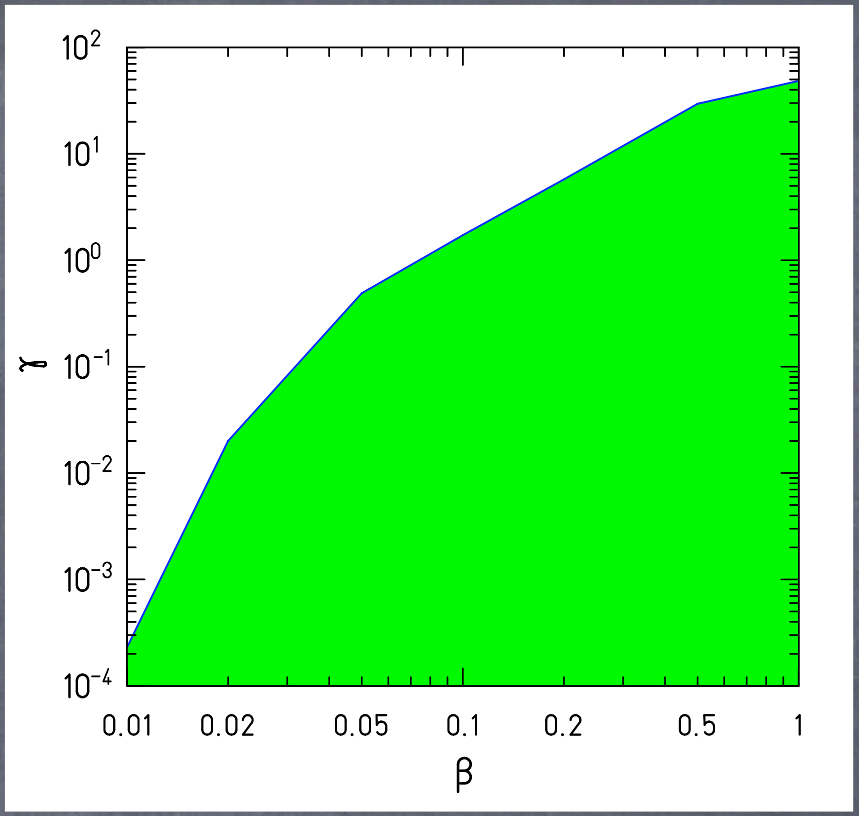
# Chameleon Searches

- Eot-Wash

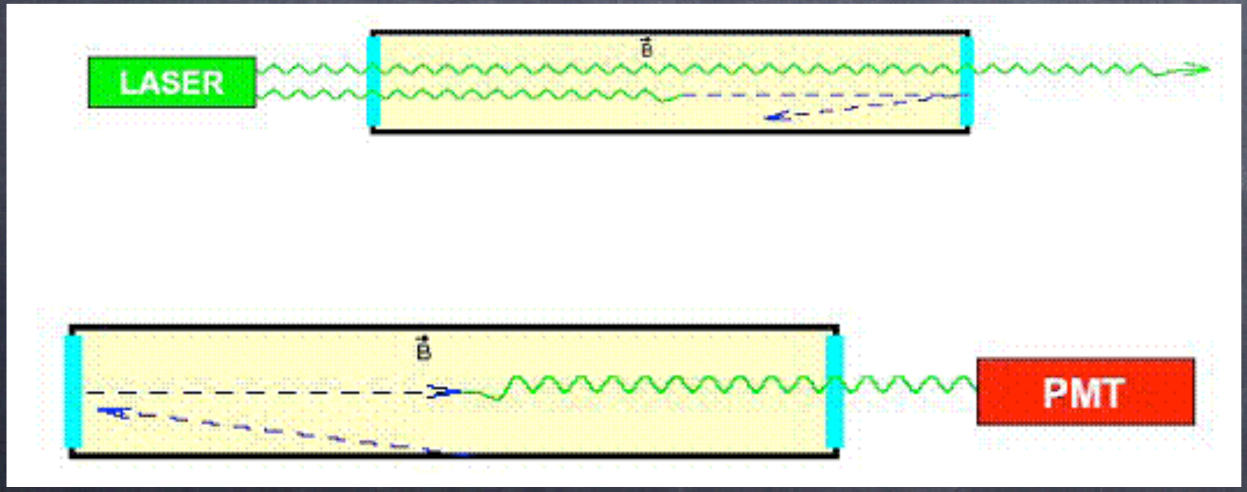
  Adelberger et al.,
  Phys. Rev. Lett. (2008)

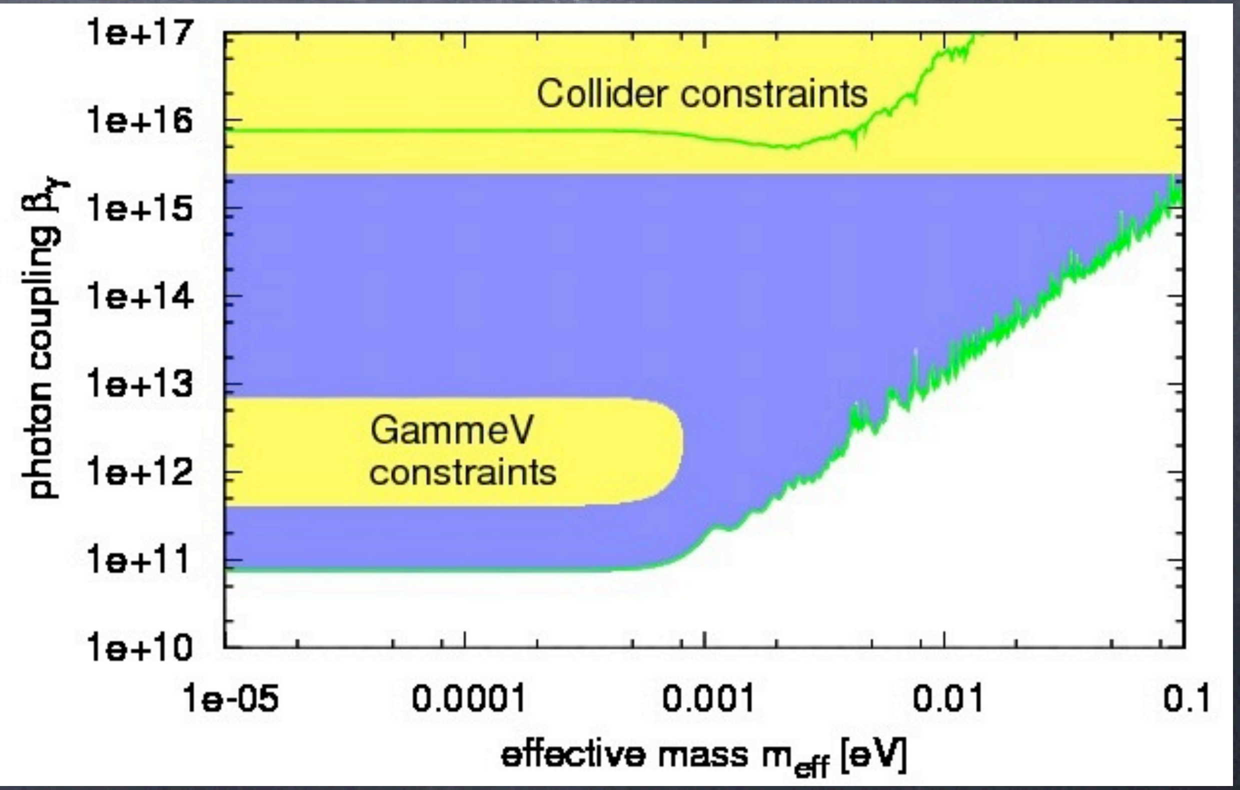





- CHameleon Afterglow SEarch (CHASE), Fermilab

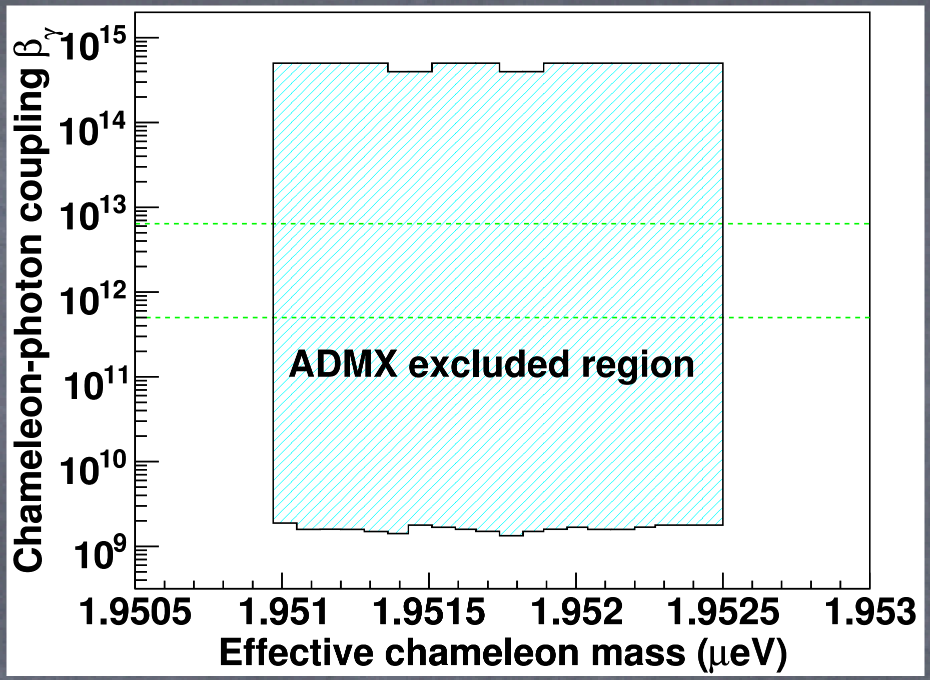
  Chou et al., Phys. Rev. Lett. (2008,2010)



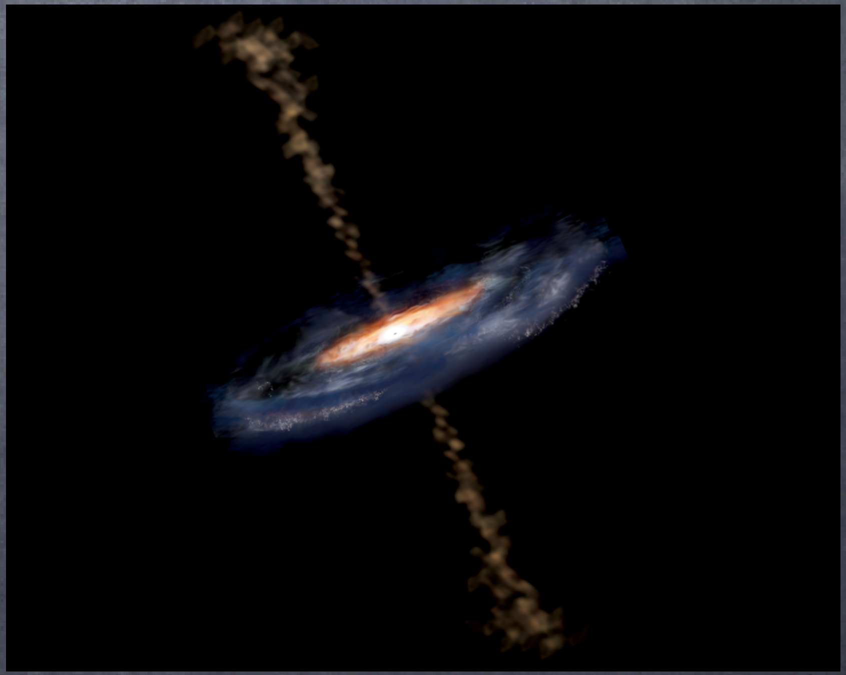
- ADMX

  P. Sikivie & co., Phys. Rev. Lett. (2010)




- Active Galactic Nuclei

  C. Burrage et al., Phys. Rev. Lett. (2009)



Photons -> Chameleon conversions increase scatter in empirical luminosity relations

$$\log_{10} Y_i = a + b \log_{10} X_i + S_i$$